Comparison of Polarimetric SAR Techniques for the Measurement of Directional Ocean Wave Spectra

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***Abstract*—Several methods have been investigated which use fully polarimetric synthetic aperture radar (POLSAR) data to measure directional ocean wave slope spectra. Independent techniques have been developed to measure wave slopes in the orthogonal SAR (azimuth/range) directions. In this paper, wave spectra measured using two polarimetric methods are investigated. Spectra developed using a) intensity-based polarimetric SAR methods and b) a more recent orientation/alpha angle algorithm are compared. NASA/JPL/AIRSAR L-band data from two-sites in California coastal waters have been used.**
***Keywords*: Radar polarimetry, directional ocean wave spectra, slick fields, and remote sensing.**

I. INTRODUCTION

Synthetic aperture radar images of waves on the ocean surface have traditionally been used with intensity-based algorithms to measure physical parameters such as wave slope spectra [1]. SAR instruments operating at a single polarization measure wave-induced backscatter cross-section modulations. These measurements require a parametrically complex modulation transfer function (MTF) to relate ocean wave properties to the SAR ocean backscatter measurements.

In this paper two methods of measuring wave spectra will be described and compared. These methods utilize 1) SAR intensity modulations measured at linear-basis polarizations [2] and 2) orientation/alpha angle modulations [3]. The alpha angle is from the Cloude-Pottier decomposition [6].

The studies reported here investigate the feasibility of using fully polarimetric SAR (POLSAR) data to improve measurement of ocean spectra in both the azimuth and range directions. In the Fourier-transform domain, this orthogonal slope information may be used to estimate a complete directional ocean wave slope spectrum.

The advantages of using these new POLSAR algorithms are that azimuth and range direction modulations are increased in strength.

II. ORIENTATION ANGLE INTENSITY MODULATION

The first polarimetric SAR technique has been investigated for improving the visibility of ocean waves, whose propagation direction has an azimuthal component. Wave-induced changes in polarimetric orientation result in significant image intensity modulations - if the quiescent measurement polarization is selected optimally.

The basis for polarization orientation modulation [2] is illustrated in Fig. 1. This polarimetric signature represents the response on the normalized backscatter intensity for any polarization (orientation/ellipticity). A profile (white strip) through the polarization signature, parallel to the orientation axis with the ellipticity $\chi = 0$ is given in Fig.1. Figure 2 shows the values of this profile, as well as, its derivative. This curve represents the backscattered response for all linear polarizations. Vertical- (transmit/receive)-pol is at $\psi = 90^o$ and horizontal-pol is at $\psi = 0^o$, or, 180^o. When an image is processed using a polarization orientation ψ ($\equiv \psi_o$) where the slope of this linear polarization curve is a maximum, the visibility of azimuthally traveling waves is enhanced. The long wave will perturb this quiescent orientation point (ψ_o) by the mean wave slope in the resolution cell. The brackets <> in Fig. 2 indicate spatial averaging. For each resolution cell the orientation modulation, is translated into a corresponding intensity modulation, $\delta I / I_0$.

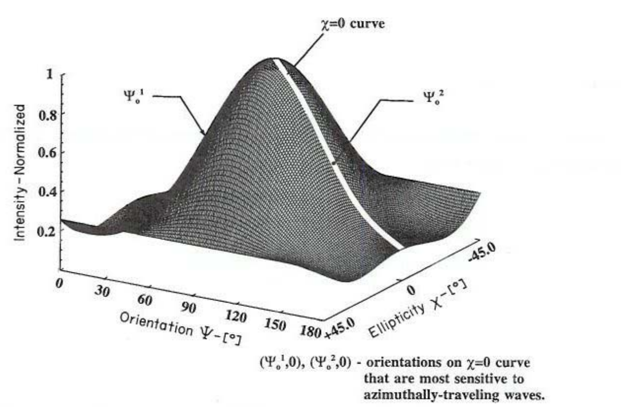

Figure 1: A polarization signature for the ocean surface (L-band, incidence angle 45°, JPL-AIRSAR) data showing intensity versus orientation and ellipticity.

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This polarization intensity modulation acts as a separate source-term for the overall microwave modulation transfer function. This technique, introduced by Schuler et al. [2,4] shows potential for making measurements on azimuthally-traveling ocean waves. Important to the success of this technique is the fact that ocean polarization signatures are 1) relatively constant in morphology, and 2) have regions with large intensity variations related to perturbations in the orientation. When an image is processed using a polarization where this variation is a maximum, tilt perturbations due to azimuthally traveling ocean waves have a significant effect on the backscattered intensity.

From Fig. 2 it can be seen that polarization orientations $\psi \equiv \psi_o$ away from HH or VV can produce large intensity modulations for resolved wave tilts in the azimuthal direction. The optimal orientation occurs at the point where the second derivative of the radar cross-section is equal to zero. This position of maximum sensitivity to azimuthal wave tilts ψ_o will vary as a function of the polarization ratio $\rho^2 \equiv S_{hh}S^*_{hh} / S_{VV}S^*_{VV}$. This effect is shown in Fig. 3(a-b). The range of polarization ratio values is 45° to about 60°.

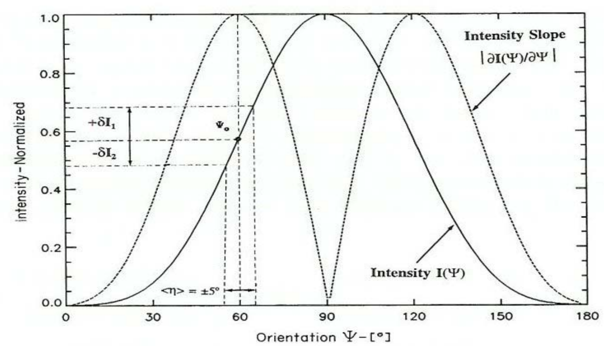


Figure 2: Concept of polarimetric orientation modulation by resolved long ocean wave systems. Shown is a linear-polarization signature. Radar transmit/receive polarization is chosen to be ψ_o degrees.

Studies using a RAR imaging model [2] indicate that undesirable effects such as spectral-splitting and distortion of the radar-image spectrum may be greatly reduced for the case of azimuthally traveling waves. Splitting of the spectrum parallel to the azimuthal direction can be almost eliminated [2]. This model allows comparisons to be made between conventional RAR spectra, and spectra developed with the polarization modulation term included. He et al [7] have developed an MTF for POLSAR intensity-based wave spectra applications. Figure 4 gives normalized values of intensity modulation, δI/ I, derived from wave spectra data for HH, VV polarizations as well as, non-standard synthesized polarizations. The HH-pol modulation is larger than the VV-pol value. The maximum modulation occurs at about 55 degrees and supports the theory.

III. ORIENTATION/ALPHA ANGLE METHOD FIRST SITE: NORTHERN CA. COASTAL WATERS

The second technique investigated uses orientation/alpha angles to measure wave slopes and spectra. AIRSAR data (1994) at L-band imaging a coastal area bordering Mendocino County in Northern California was used to determine if the azimuth component of an ocean wave spectrum could be measured using orientation/alpha angle modulation. A wave system with an estimated dominant wavelength of 156m was propagating through the site with a wind/wave direction of 320° (NDBC Buoy, Bodega Bay). Modulations in the polarization orientation angle induced by azimuth traveling ocean waves in the study area were visible in the scene

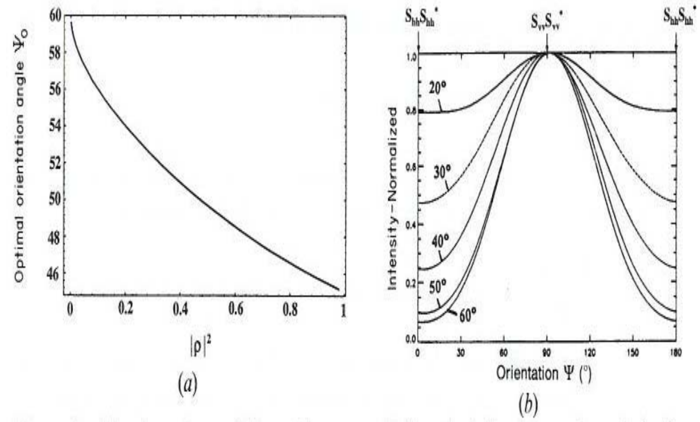


Figure. 3(a-b) Dependence of the optimum sensitivity orientation ψ_o on the polarization ratio $S_{hh}S^*_{hh}/S_{vv}S^*_{vv}$ a) and, variation of the ocean linear polarization. signature with incidence angle b).

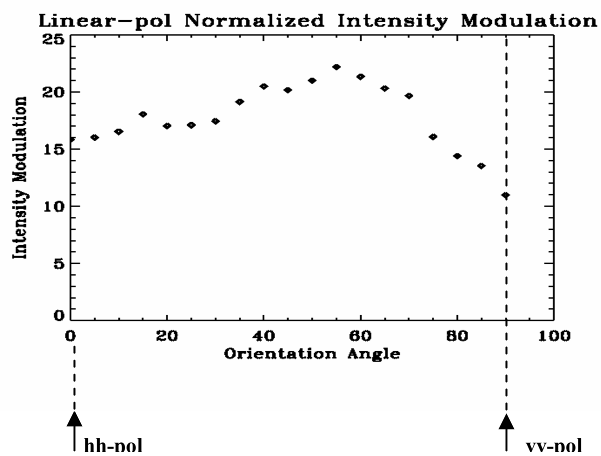


Figure 4: Wave Spectra intensity modulation δ I/I versus orientation angle for a range of synthesized linear polarizations of 0°-90° in 5 deg. steps..

It has been shown by Schuler et al [3] that by measuring the orientation angle shift in the polarization signature one may determine a combined effect of the range/azimuth surface tilts. In particular, the shift in the orientation angle is related to the range/azimuth surface tilts and the local incidence angle. This relationship, derived by Lee [5] and Pottier [6] is

$$\tan \theta = \frac{\tan \omega}{\sin \phi - \tan \gamma \cos \phi} \quad . \qquad (1)$$

where, θ, $tan\omega$, $tan\gamma$, and ϕ are the shift in the orientation angle, the azimuth slope, the ground range slope, and the radar incidence angle, respectively. According to (1), the azimuth tilts may be estimated from the shift in the orientation angle, if the range tilt is known. The orthogonal range slope can be estimated using the value of local incidence angle associated with alpha for each pixel. Since for the ocean surface, the tilt angles are small, the denominator in (1) may be approximated by $\sin\phi$. Thus, for the ocean surface, the azimuth slope may be written as

$$\tan\ \omega \approx (\sin\ \phi) \cdot \tan\ \theta\ . \qquad (2)$$

Combining the azimuth slope, tan ω and range slope tan γ provides complete slope information for each image pixel.

A. Orientation Angle (Azimuth) Spectra

POLSAR data can be represented for single-look complex data by a scattering matrix and multi-look complex data, by a covariance (or coherency) matrix. An orientation angle shift causes rotation of all these matrices about the line of sight. Since the orientation angle information is embedded in the POLSAR data, several methods have been developed to estimate azimuth slope induced orientation angles for the land and sea. The "polarization signature" method and the "circular polarization" methods have proven to be the two most effective. A complete discussion of these methods and the relation of the orientation angle to orthogonal slopes and radar parameters are given in Lee *et al.* [5]. Figure 5 shows an orientation angle wave spectra. with wavenumber plotted radially. The white rings are located at 50m intervals. The dominant wave, a wavelength of 153 m, is marked in red.

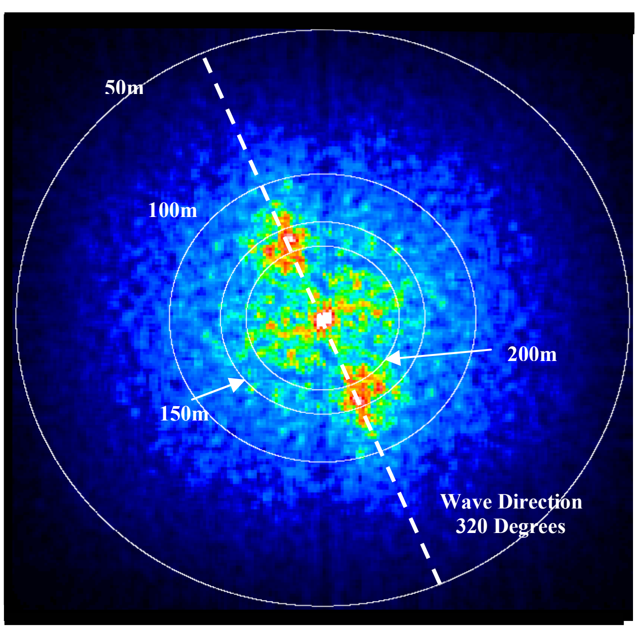


Fig. 5: Orientation angle spectra vs. wavenumber for azimuth direction waves propagating in the CA. coastal study area.

Figure 6a) presents a profile through the orientation angle spectrum made in the direction (320°) of maximum spectral energy. Figure 6b) is a similar profile but is derived for a conventional vv-pol image SAR intensity spectrum. It is apparent that the orientation angle spectrum has a higher dominant wave spectral peak/background ratio. The ratio of the value at the spectral peak divided by the DC value is used as a measure of the normalized change in cross-section.

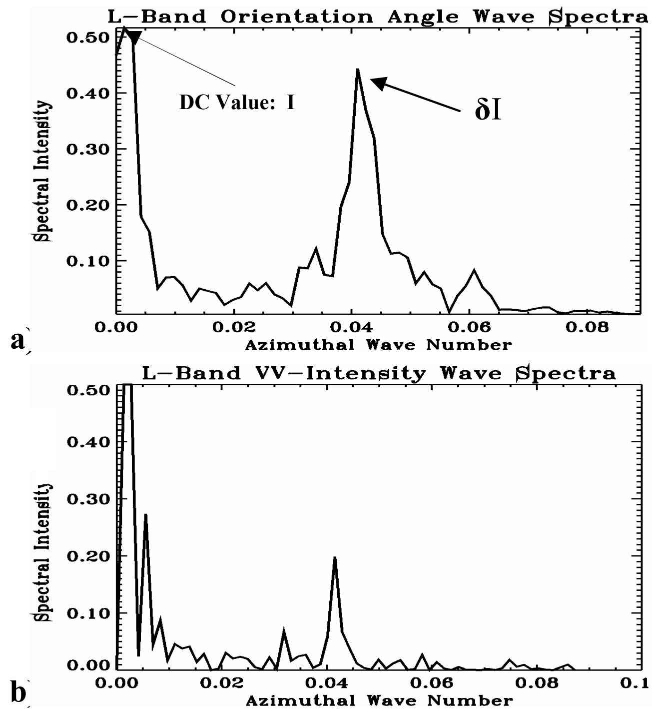


Fig. 6 (a-b): Plots of spectral intensity vs. wavenumber a) for wave-induced orientation angle modulations, and b) VV-pol intensity modulations.

B. Alpha Parameter (Range) Spectra

Several concepts have been proposed for physically-based POLSAR measurements of ocean slopes in the range direction. These concepts were developed as a means of circumventing some of the difficulties associated with conventional backscatter intensity-based methods.

The alpha (α) parameter, developed from the Cloude-Pottier <<H/A/α>> polarimetric decomposition theorem [6], has desirable properties: 1) It is roll-invariant in the azimuth direction and, 2) in the range direction it is sensitive to wave-induced modulations ($\delta\phi$) in the local incidence angle ϕ. Thus, the measurements are well de-coupled.

Wave spectra may be sensed using the alpha parameter. An image of the study area may be formed with the mean of α (ϕ) removed line by line in the range direction. An FFT of the study area results in a wave spectrum that is very similar to the spectrum of Fig. 5. This spectrum can be converted to a range wave slope spectrum.

Model studies [3] resulted in an estimate of what the parametric relation, α vs. incidence angle ϕ, should be for an assumed Bragg-scatter model. The sensitivity (i.e., the slope of the curve of $\alpha(\phi)$) was large enough to warrant further study using real POLSAR ocean backscatter data. A curve of α vs. incidence angle ϕ was developed for the Mendocino Co. AIRSAR data. This curve shows a high sensitivity for the slope of α (ϕ). A wave spectra similar to Fig. 5) was developed for the alpha parameter technique and a dominant wave was measured having a wavelength of 154m and a propagation direction of 320 ^{o}.

IV. ORIENTATION/ALPHA ANGLE METHOD . SECOND SITE: SANTA CATALINA ISLAND

A) Measurement of Wave Spectra in Slick Fields

Wave spectral measurements are frequently contaminated when the ocean surface contains biogenic, or man-made, slicks. The non-intensity based techniques of Section III are not significantly affected by slicks unless the Bragg back-scatter falls below the SAR noise-floor. This capability for the orientation/alpha angle modulation techniques will allow measurements of wave spectra to be made in slick-covered waters such as those off the coast of California.

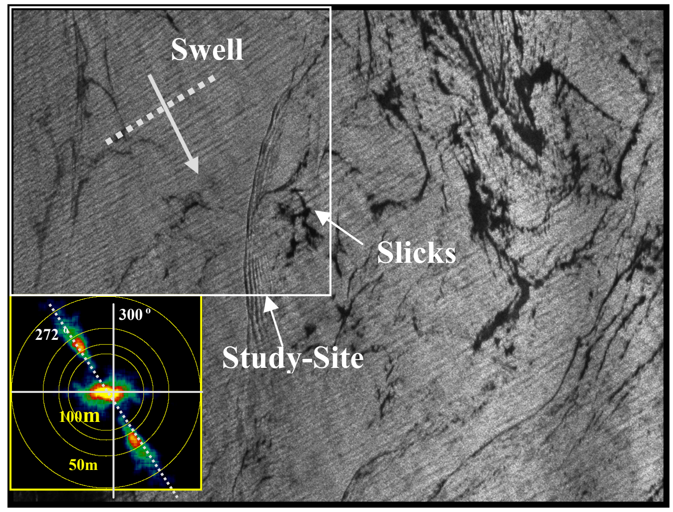
B. AIRSAR Spectra Measurements in a CA. Slick Field

Measurements of Pacific swell at a second site near Santa Catalina Island were carried out by the Naval Research Laboratory in 2003. NASA/JPL/AIRSAR L – band ocean scatter data, CM6748 on 4/19/2003, from the study-site has been inputted to previously developed wave measurement algorithms.

The new results are given in Fig. 7 for the swell wavelength, swell direction, and rms wave height. The nearest source of comparison, an NDBC 3-meter discus (Santa Monica Basin Station - 46025) buoy was 38km away from the study-site in deeper water. This buoy did not make directional wave measurements, but did measure an average dominant wave period of 6.2 sec. Such a period would, correcting for depth effects, correspond to a wavelength of 62m at the study site, compared to the 67m that was measured. The rms wave height measured by the buoy averaged 1.3m, compared with the directional radar measurement of 1.62m.

V. CONCLUSIONS

Methods have been investigated which are capable of measuring ocean wave spectra in both the range and azimuth directions.. The polarization modulation used in both of the techniques presented here enhances the ability to measure azimuthal ocean waves using POLSAR. The polarimetric measurements of orientation/alpha angle modulation are the most accurate and sensitive. The techniques are most effective when making measurements of long ocean waves and swell. Secondly, spectral distortion is lowest when the measurements are made at high incidence angles. The ability of the orientation/alpha angle techniques to accurately measure wave spectra in the presence of coastal slick fields is potentially of considerable importance.



Wave Spectra

Figure 7: Orientation/Alpha wave spectra of Pacific swell propagating towards a slick field off of Santa Catalina Island. Wave field parameter values were derived from the wave spectrum and orientation/alpha angle algorithms.

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